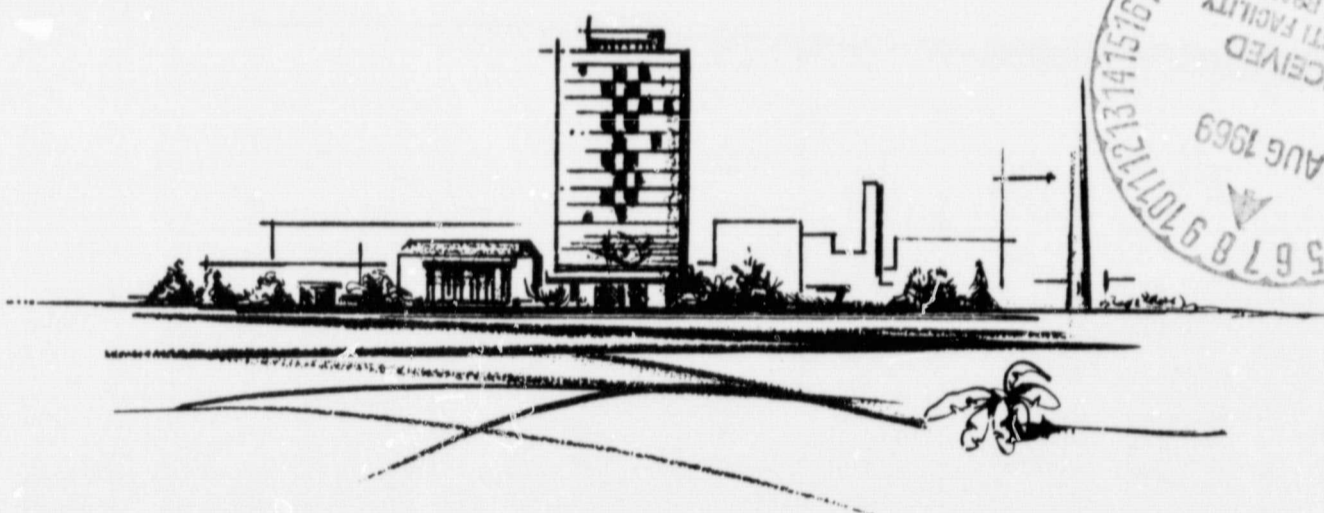
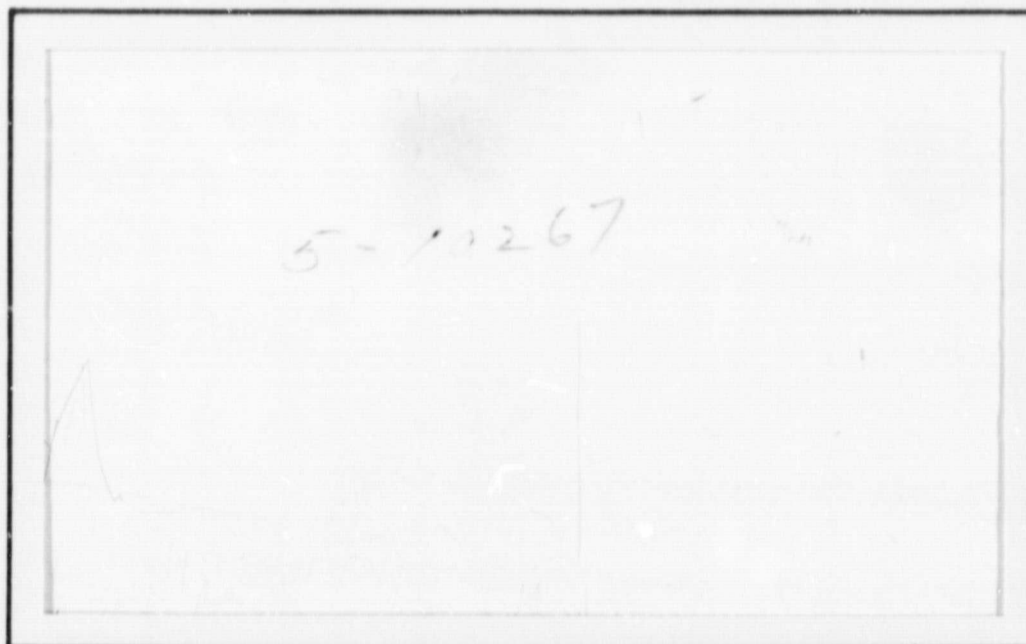


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# RESEARCH REPORT



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SUMMARY REPORT

on

CONTINUATION OF A STUDY

of

STABILITY OF STRUCTURAL MATERIALS FOR  
SPACECRAFT APPLICATIONS FOR THE ORBITING  
ASTRONOMICAL OBSERVATORY PROJECT

to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
GODDARD SPACE FLIGHT CENTER

July 15, 1969

by

C. W. Marschall, M. E. Hoskins, and R. E. Maringer

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July 15, 1969

National Aeronautics and Space Administration  
Goddard Space Flight Center  
Glenn Dale Road  
Greenbelt, Maryland 20771

Attention Mr. F. J. Cepollina  
Code 410

Dear Mr. Cepollina:

Enclosed are 25 copies of our Summary Report on "Continuation of a Study of Stability of Structural Materials for Spacecraft Applications for the Orbiting Astronomical Observatory Project". This report summarizes the work accomplished to date. Work is continuing and will be reported in biweekly letters.

Should you have any questions, please call me at Extension 2857 or Dr. C. W. Marschall at Extension 3464.

Very truly yours,

*R. E. Maringer*

R. E. Maringer  
Chief, Mechanical Metallurgy  
Division

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SUMMARY REPORT  
on  
CONTINUATION OF A STUDY  
of  
STABILITY OF STRUCTURAL MATERIALS FOR  
SPACECRAFT APPLICATIONS FOR THE ORBITING  
ASTRONOMICAL OBSERVATORY PROJECT

SUMMARY

This report describes work in progress at Battelle to study the dimensional stability of 2014-T6 aluminum and 321 stainless steel. Several types of experiments are being conducted to evaluate: (a) micro-yield strength, (b) stress relaxation accompanying thermal cycling, (c) stress relaxation accompanying stress cycling, and (d) microcreep at room temperature.

The results available to date indicate that 2014-T6 aluminum has a number of attractive properties for spacecraft applications in which dimensional stability is important. It has a relatively high MYS-to-density ratio and apparently relaxes very little under moderate thermal cycling or rapid stress cycling when stressed to a high percentage of its MYS. It does exhibit some microcreep, however, when stressed to 90 percent of MYS at 68 F.

The annealed 321 stainless steel appears less attractive for dimensionally critical spacecraft applications. It has a low MYS-to-density ratio and relaxes appreciably under moderate thermal cycling. Its behavior under stress cycling is not yet known. Room temperature creep at 90 percent of MYS does not appear to be significant after ~ 100 hours.

### INTRODUCTION

Dimensional stability is an extremely important property for certain structural components in NASA's orbiting astronomical observatory project. Studies conducted previously at Battelle under Contract No. NAS5-10267 indicated that residual stresses and their gradual relaxation with time are responsible for much of the observed dimensional instability in structural materials.

One obvious way to achieve dimensional stability is to avoid residual stresses completely. This is difficult to accomplish, however, because residual stresses are known to accompany various manufacturing operations, including heat treatment, machining, forming, and joining. It is important, therefore, in dimensionally critical applications, that either we find ways to relax these residual stresses prior to placing components in service or we convince ourselves that the residual stresses will not relax, even in very long times, under the conditions experienced by the component in service.

With respect to operating conditions in an orbiting observatory, the temperatures experienced are near normal room temperature and are not what one would usually consider severe with respect to stress relaxation. However, temperatures can be expected to cycle between about -50 and +100 F in each night-day sequence; there is considerable evidence to indicate that thermal cycling can accelerate stress relaxation processes. Additionally, mechanical vibrations (or stress cycling) may be experienced during launch of the observatory and to a lesser extent during orbit.

Here again, there is much evidence to indicate that stress relaxation may be accelerated by mechanical vibrations. It is one of the primary objectives of this investigation to evaluate the effectiveness of thermal cycling and stress cycling in accomplishing stress relaxation.

An additional source of dimensional stability in a structural component is plastic deformation under an imposed stress. This could be a short-duration stress, such as would be associated with g-forces developed during launch of an orbiting observatory, or a long-term stress, as in a load-bearing member. Thus, in addition to studying the role of thermal cycling and stress cycling in stress relaxation, this investigation is also concerned with evaluating the microyield strength (MYS, the stress required to produce a permanent strain of one microinch per inch) and the room temperature microcreep behavior of spacecraft structural materials.

This report describes Battelle's approach toward obtaining the desired dimensional stability information for two materials (2014-T6 aluminum and annealed 321 stainless steel) and presents the results obtained to date. In addition to the studies on aluminum and stainless steel, I400 beryllium from an earlier NASS-Goddard sponsored investigation is being studied to a limited extent in this program.

#### MATERIALS BEING INVESTIGATED

The materials being investigated in this program, 2014 aluminum and 321 stainless steel, were furnished to Battelle by Goddard Space Flight Center. The 2014 aluminum was supplied in the form of 1/8-inch sheet in the O-condition. It was subsequently heat treated at Battelle to the T6

condition\*, prior to machining specimens. Although this was an alclad material (cladding thickness approximately 0.005-inch), the cladding was removed at Battelle in the course of specimen preparation. Consequently, the cladding played no role in the property measurements.

The 321 stainless steel was furnished to Battelle as 3/16-inch sheet in the stabilized annealed condition. The stabilizing heat treatment, to prevent deterioration of corrosion resistance after welding or after exposure to temperatures in the range 750 to 1600 F, consists of holding at 1600-1650 F for 2 to 4 hours, followed by rapid cooling.

With respect to the chemical composition and mechanical properties of these materials, 2014 aluminum is a high strength alloy containing nominally 4.4 percent Cu, 0.8 percent Si, 0.8 percent Mn, and 0.4 percent Mg. Typical mechanical properties for this alloy in the T6 condition are:

Yield Strength	60,000 psi
Tensile Strength	70,000 psi
Elongation	13 percent
Hardness	Rockwell B 80 to 86

Type 321 stainless steel is a grade containing titanium to stabilize any carbon present in the alloy. The nominal composition is:

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\* To obtain the T6 condition, the 2014 aluminum was first solution treated by heating to 935 F for one hour and water quenching; it was then precipitation hardened by heating to 340 F for 10 hours and air cooling.

Carbon	0.08 percent (maximum)
Chromium	17-19 percent
Nickel	9-12 percent
Titanium	5 X percent Carbon (minimum)

The vendor's test report on the 3/16-inch 321 stainless steel sheet supplied to Battelle by Goddard Space Flight Center shows the following mechanical properties:

Yield Strength	42,600 psi
Tensile Strength	87,200 psi
Elongation	52 percent
Hardness	Rockwell B 82

In addition to the 2014 aluminum and the 321 stainless steel, several samples of 1400 beryllium are also being investigated for stress relaxation under cyclic stressing in this program. These are samples remaining from an earlier NASA-Goddard sponsored program at Battelle. The samples were originally machined from 1 x 4 x 2.5-inch hot-pressed block, etched, thermally stress-relieved at 1100 F for one hour, and subsequently used in room-temperature microcreep studies below the MYS.

#### DESIGN AND PREPARATION OF TEST SPECIMENS

Several types of experiments are being conducted to evaluate:

- a) Microyield strength
- b) Stress relaxation accompanying thermal cycling

- c) Stress relaxation accompanying stress cycling
- d) Microcreep at room temperature.

The procedures being followed and descriptions of test specimens are discussed in subsequent paragraphs.

Specimens to Evaluate Microyield Strength, Stress Relaxation Accompanying Stress Cycling, and Microcreep

Specimens to evaluate microyield strength, stress relaxation accompanying stress cycling, and microcreep, are flat, pin-loaded tensile specimens 3-1/2-inches long by 7/8-inch wide. They have a reduced section 1/4-inch wide by 1-1/8-inch long. The thickness of the reduced section differs slightly among the three materials being studied; approximate thicknesses are: aluminum and beryllium specimens, 0.110-inch; stainless steel, 0.140-inch. The aluminum and stainless steel specimens are cut from the starting sheet with their long dimension perpendicular to the rolling direction. They are then ground equally from both sides to a thickness approximately 0.010-inch greater than the finish dimension. The specimens are then chemically etched in the reduced section to remove machining damage. Etching details are as follows:

2014 Aluminum

Etching solution

Sodium hydroxide (NaOH)	100 g
Water	500 cc
Bath temperature	110 F

Smut removal solution

10 percent  $\text{HNO}_3$  in water

321 Stainless Steel

## Etching solution

Aqua Regia (3 HCl : 1 HNO<sub>3</sub>)

Bath temperature

RT

Approximately 0.010-inch is removed from the thickness in this operation (0.005-inch per side). This is followed by thermal stress relieving for one hour, followed by a furnace cool. Stress relieving temperatures are 400 F for 2014 aluminum\* and 750 F for 321 stainless steel.

Electrical resistance strain gages, manufactured by Micromasurements Company, are then applied to both sides of the specimen reduced section. The types of gages employed for each material and type of specimen are tabulated below:

Type of Specimen	Micromasurements Company Gage		
	Identification Number for Material Indicated		
	2014 Al	321 S.S.	1400 Re
MYS	EA-13-250BG-120	EA-09-250BG-120	Not Applicable
Creep	EA-13-250BG-120	EA-09-250BG-120	Not Applicable
Stress Cycling	WK-13-250BP-120	WK-09-250BP-120	WK-06-250BP-120

Gages are bonded to the specimens with W. T. Bean Company's BR-600 cement. The cement is cured at 225 F for one hour.

\* It should be recognized that stress-relieving 2014-T6 aluminum at 400 F results in an overaged condition (i.e., reduced strength) that can no longer be properly referred to as T6. This stress relieving temperature was selected on the basis of data in the literature and results of previous work at Battelle, as suitable for achieving a reasonable degree of stress relief in a short time without drastically lowering the strength.

Specimens to Evaluate Stress Relaxation  
Accompanying Thermal Cycling

Two types of specimens are being employed to study stress relaxation accompanying thermal cycling. One is a disk specimen with lapped surfaces suitable for interferometric measurements. Disk dimensions are 1.0-inch diameter by 0.110-inch thick for aluminum specimens and 1.25-inch diameter by 0.130-inch thick for stainless steel specimens. The other type of specimen is a thin, rectangular strip which is bent to a fixed and measurable radius, thus imposing known stresses, while being subjected to thermal cycling. Strip dimensions are 4 x 0.5 x 0.020-inch.

Sample preparation procedures, including grinding, etching, and thermal stress relieving, are virtually identical to those described earlier for the flat tensile specimens. The major exception involves the disk specimens; after the thermal stress relief treatment, the disks are lapped flat and parallel in a Do-All parallel lapping machine, which is designed to lap multidirectionally. A second exception concerns the etching solution used on the strip specimens of 321 stainless steel: to achieve improved control on etching rate and surface smoothness, the following solution was used:

HNO <sub>3</sub>	20 percent (by volume)
HF	10 percent
Water	70 percent

## EXPERIMENTAL PROCEDURES AND RESULTS

### Measurement of Microyield Strength

A detailed description of the procedures followed in conducting microyield strength (MYS) tests was provided in an earlier Battelle report.\* Briefly, the procedure consists of loading the specimen in tension to a low stress, removing the load, and measuring the residual strain to the nearest 0.1 microinch/inch with a BLH Model 120 strain indicator connected to the strain gages on the specimen. The specimen is then reloaded to a slightly higher stress, unloaded, and the residual strain measured as before. The procedure is repeated, with the load increasing incrementally with each cycle, until residual strains of at least 50 microinches/inch are recorded. In several cases, these tests were continued to much larger strains, of the order of 10,000 microinches/inch. A logarithmic plot of stress versus residual strain is prepared from the data; from this graph, the microyield strength value, i.e., the stress corresponding to a residual strain of one microinch/inch, is obtained.

Microyield strength values obtained in this study are shown in Table 1. The MYS of the 2014-T6 aluminum (37,000 to 39,000 psi) is surprisingly high and exceeds the values measured for other aluminum alloys in our earlier investigations for Goddard. MYS values obtained in that

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\* Maringer, R. E., Cho, M. M., and Holden, F. C., "Stability of Structural Materials for Spacecraft Application", Battelle Memorial Institute, Final Report to Goddard Space Flight Center, Contract No. NAS5-10267, April 16, 1968.

study were 29,000 to 35,500 psi for 2024-T4 aluminum and 25,400 to 27,200 psi for 6061-T6 aluminum, after stress relieving at 400 F for one hour.

TABLE 1. MEASURED MICROYIELD STRENGTH VALUES

Material	MYS, psi
2014-T6 Al	39,000
	38,000
	37,000
321 Stainless Steel	9,600
	9,600
	11,300

The measured MYS values for 321 stainless steel, on the other hand, are disappointingly low (9600 to 11,300 psi).

In addition to the MYS data shown in Table 1, obtained on specimens that were etched and thermally stress relieved after machining, several MYS tests were conducted on 2014-T6 aluminum specimens in the as-machined condition to see the effect of machining-stresses on the MYS\*. Three tests gave the following MYS values:

42,000 psi  
39,000 psi  
44,000 psi.

\* To facilitate comparison with the results shown in Table 1, the specimens tested in the as-machined condition were heated to 400 F for one hour prior to machining.

These are, on the average, several thousand psi greater than those obtained on specimens in which machining damage had been removed. Although one could guess at possible mechanisms for this behavior, the reasons for the strengthening effect associated with a thin layer of machining-damaged material are not presently known.

On one sample each of 321 stainless steel and 2014-T6 aluminum, MYS tests were continued to larger residual strains (approximately 10,000 microinches/inch) than were previous tests, to check the hypothesis that all the data points for a particular specimen will fall on a single straight line when plotted logarithmically. If this hypothesis were true, it would mean that MYS values for ductile materials could be obtained simply by extrapolating logarithmic stress-strain curves from the macrostrain region to the microstrain region. The results of the two tests described above indicate that the data points do not describe a single straight line on a logarithmic plot, although the aluminum data come closer to doing this than do the stainless steel data. In both cases, the MYS values obtained by extrapolation are greater than those actually measured. Thus, at the present time, there appears to be no simple reliable method for predicting microproperties from macroproperties.

#### Measurement of Stress Relaxation Accompanying Thermal Cycling

##### Strip Specimens Stressed in Bending

In these experiments, rectangular strip specimens 4 x 0.5 x 0.020-inch are bent over a mandrel to a preselected radius, such that the stresses

in the outer fibers of the specimens are 80 to 90 percent of the MYS. The specimens are held at this bend radius while subjected to thermal cycling. After thermal cycling, the specimen is removed from the mandrel; the residual curvature, if any, is a measure of the extent of stress relaxation.

The procedure followed in conducting an experiment of this type includes the following steps:

1. Prepare the specimens as described earlier.
2. Measure specimen thickness to the nearest 0.0001-inch at several locations.
3. Measure the initial flatness of the specimen.
4. Prebend the specimen onto the mandrel at room temperature and remove it from the mandrel immediately; measure the residual curvature, if any, accompanying this operation.  
  
(Note: if the specimen is not perfectly flat initially, the bend is imposed in the same direction as the initial curvature).
5. Bend the specimen onto the mandrel and clamp into place with a thin cover plate (approximately 0.050-inch thick). Place the entire assembly in a thermal cycling oven (Model SK-3102, Environmental Test Chamber, Associated Testing Laboratories, Inc.), where it is subjected to a preselected temperature cycle.
6. After thermal cycling, remove the specimen from the mandrel and measure the residual curvature.

Measurement of initial and final specimen curvature is accomplished in a support fixture containing two knife edges separated by 3.5 inches. The strip specimen is centered on the knife edges and a Sheffield high-amplification electronic height gage with a strip-chart recorder is used to traverse the specimen over the 3.5-inch span. All measurements are performed in an environmentally controlled laboratory at  $68 \pm 0.25$  F. Instrument calibrations are made with Laboratory Grade gage blocks.

The height gage has a cylindrical stylus of 0.0625-inch diameter and a gaging pressure of 5 grams. This stylus pressure is sufficient to bend the thin strip specimens a significant amount during measurement, particularly when the traverse reaches mid-span; this poses no serious problem, however, because this bend deflection can be subtracted out by turning the specimen over and measuring from the opposite side. If  $h_1$  is the apparent bow height over a 3.5-inch span measured on one side of the specimen and  $h_2$  is the apparent bow height measured on the opposite side of the specimen, the actual bow height,  $h$ , is simply

$$h = \frac{h_1 - h_2}{2} . \quad (1)$$

The mandrel over which the strip specimen is bent is designed to produce an outer fiber stress in the specimen of approximately 90 percent of the MYS. The outer fiber stress ( $\sigma$ ) is a function of thickness ( $t$ ), Young's modulus ( $E$ ), and bend radius ( $\rho$ ). If the specimen is initially perfectly flat,

$$\sigma = \frac{tE}{2\rho_b} . \quad (2)$$

For a thickness of 0.020-inch and Young's modulus values of  $10.6 \times 10^6$  and  $28 \times 10^6$  psi for aluminum and stainless steel, respectively, the required bend mandrel radii are:

<u>Specimen Material</u>	<u>Outer Fiber Stress, psi</u>	<u>Mandrel Radius, inch</u>
Aluminum	34,000 (90% of MYS)	3.12
Stainless steel	8,650 (90% of MYS)	32.4

Mandrels were prepared to the above radii, using materials whose thermal expansion coefficients matched closely those of the strip specimens. Cover strips to hold the specimens down on the mandrel were likewise prepared from material of matching coefficients and were kept thin (0.050-inch) to facilitate heat transfer to and from the specimen during thermal cycling.

The stress actually induced in the strip specimen when bent over the mandrel is frequently less than that shown in the above tabulation, because of some initial curvature in the specimen. This stress can be approximated closely by

$$\sigma = \frac{tE}{2\rho_b} - \frac{tE}{2\rho} \quad (3)$$

where  $\rho$  is the initial radius of curvature. The value of  $\rho$  can be obtained from the measured initial bow height ( $h$ ) by simple geometric considerations and assuming a span length of 3.5-inches:

$$\rho^2 = \left(\frac{3.5}{2}\right)^2 + (\rho-h)^2 \quad (4)$$

When  $h$  is small, Equation 4 reduces to

$$\rho = \frac{1.53}{h} \quad (5)$$

Substituting this into Equation 3 gives

$$\sigma = \frac{tE}{2} \left[ \frac{1}{\rho_b} - 0.653 h \right] \quad (6)$$

When  $h = 0$ , Equation 6 reduces to Equation 2.

The amount of stress relaxation or decrease in stress ( $\Delta\sigma$ ) at constant strain can be obtained from the initial bow height ( $h$ ) and the final bow height ( $h_f$ ) from the relationship

$$\Delta\sigma = \frac{tE}{2\rho_f} - \frac{tE}{2\rho} = \frac{tE}{2} \left[ \frac{h_f - h}{1.53} \right] = 0.327 tE(h_f - h) \quad (7)$$

Results obtained on relaxation of known stresses by thermal cycling are summarized in Table 2. Based on these preliminary results, several observations appear warranted:

1. The technique employed, while relatively simple, is capable of detecting stress relaxation of very small magnitudes.
2. The stress relaxation accompanying 12 thermal cycles from -50 to +100 F is substantially greater for 321 stainless steel than for 2014-T6 aluminum (3 to 4 percent versus 0.1 percent).
3. The 321 stainless steel assumes a detectable permanent set in the initial rapid bend and unbend, even though the bend geometry indicates that the stress is substantially below MYS. The reason for this initial set is not known at the present time.

TABLE 2. RELAXATION OF KNOWN STRESSES  
BY THERMAL CYCLING

The thermal cycle was from -50 to + 100 F  
and the time per cycle was two hours.

Specimen Identification	Initial Stress <sup>(a)</sup> Imposed in Bend Fixture, psi	Stress Drop Accompanying Steps Indicated, psi		
		Rapid Bend & Unbend at 68 F	12 Thermal Cycles	24 Thermal Cycles
2014-A1-1	31,400 (83% of MYS)	N.D. <sup>(b)</sup>	28(0.09%)	32(0.10%)
2014-A1-2	33,400 (88% of MYS)	5(0.015%)	45(0.135%)	N.D.
321-SS-A	7,900 (82% of MYS)	28(0.35%)	263(3.33%)	N.D.
321-SS-B	7,670 (80% of MYS)	90(1.17%)	310(4.04%)	N.D.

(a) The stress shown is that in the outer fibers of the bent strip specimen.

(b) Not determined.

4. Increasing the number of thermal cycles from 12 to 24 produced virtually no additional stress relaxation in the one specimen of 2014-T6 aluminum evaluated.

Additional studies are in progress to

1. Evaluate stress relaxation associated with a more severe thermal cycle (-100 to + 200 F);
2. Evaluate stress relaxation associated with holding a stressed specimen at a constant temperature (the maximum temperature of the thermal cycle) for times comparable to those employed in thermal cycling; this should indicate the relative effectiveness of thermal cycling and constant temperature holding in inducing stress relaxation.

Disk Specimens

In this set of experiments, thin disks, machined and stress relieved according to procedures described earlier, are lapped on both sides to provide a suitable surface interferometry. One side is chemically etched away to a known depth. The resulting distortion of the interferometric pattern of the opposite face indicates the residual stress pattern associated with lapping. The specimen is then subjected to thermal cycling and reexamined to see whether any relaxation of lapping stresses has accompanied the thermal cycling. Some of the samples are then ground on the etched surface; the nature of the stresses introduced by grinding should be revealed by examination of the lapped surface. As before, these specimens will be subjected to thermal cycling to see the effect on the grinding stresses.

A Davidson Plano-Interferometer, employing a mercury discharge lamp filtered for the green line (5460 Å) or 10.7 microinch fringe interval, is used to evaluate surface flatness. Both lapped surfaces are examined initially and the side having the poorer flatness is subjected to the etching and grinding sequences. The interference fringe pattern of the better surface is recorded photographically before and after the opposite surface is etched, thermal cycled, and ground. At the same time, the maximum deviation from true flatness in a given direction, measured with filar microscope fringe splitter, is recorded.

Preliminary results are presented in Table 3. As expected, the 2014 aluminum specimens assume a convex curvature on the unetched face when material is etched away from the opposite face. This indicates that

the etching removes a layer of material that had previously been biaxially stressed in compression. Thermal cycling of the etched disks has been accomplished on only one specimen; in this 2014 aluminum specimen, only a very slight change in surface contour was observed. Additional tests are in progress.

The only data presently available for 321 stainless steel disks show that, contrary to expectations, these specimens assume a concave curvature on their unetched face when the opposite side is etched away. This is being studied further.

Additional experiments are in progress to

1. Study the effect of etching on surface flatness on a greater number of samples;
2. Study the effect of thermal cycling on surface flatness after etching one side; both -50 to +100 F and -100 to +200 F cycles will be employed;
3. Study the effect of grinding the etched face on the flatness of the opposite face.

TABLE 3. RESULTS OF TESTS ON LAPPED DISK SPECIMENS

The thermal cycle was from -50 to +100 F  
and the time per cycle was two hours.

Specimen Identification	Surface Treatment	Maximum Deviation From Flatness, microinch
2014 A1-20	None; as lapped	5 (convex)
	Etch 0.007-inch from one face	35 (convex)
	Thermal cycle 12 times	35 (convex); slight decrease in one direction to 29
	Thermalcycle additional 13 times	35 (convex); slight decrease in one direction to 29
2014 A1-3	None; as lapped	2 (concave)
	Etch 0.0007	9 (convex)
	Etch 0.0026 (total)	16 (convex)
	Etch 0.0048 (total)	32 (convex)
	Etch 0.0079 (total)	55 (convex)
321 SS-1	None; as lapped	8 (convex)
	Etch 0.0007	18 (convex)
	Etch 0.0020 (total)	35 (concave)
	Etch 0.0042 (total)	107 (concave)
	Etch 0.0080 (total)	205 (concave)

Measurement of Stress Relaxation  
Accompanying Stress Cycling

In these experiments, flat pin-loaded tensile specimens with electric resistance strain gages on both sides are subjected to a tensile load to simulate a residual stress in the material. Superimposed on this tensile load is a rapidly cycling load (1725 cycles/minute) to simulate mechanical vibration. The sum of the steady load and cyclic load is such that the maximum stress carried by the specimen is about 90 percent of the MYS. Two different stress combinations are being studied, tabulated below as percentages of the MYS:

<u>Mean Stress,</u> <u>% of MYS</u>	<u>Alternating Stress,</u> <u>% of MYS</u>	<u>Stress Range,</u> <u>% of MYS</u>
80	10	70 to 90
50	40	10 to 90

The procedure followed is to subject the specimen to a known number of stress cycles, unload it, and measure the residual strain, if any, using the same techniques and strain indicating devices as employed in measuring the MYS. The specimen is then subjected to additional cycles of the same stress magnitudes, and is again checked for residual strain. This is continued until the specimen has been subjected to about 100,000 stress cycles.

To date, only 2014-T6 aluminum specimens have been tested in this way. Results are shown in Table 4. They indicate that very little stress relief is accompanying the stress cycling. At both stress ranges

TABLE 4. RESULTS OF STRESS CYCLING TESTS ON  
2014-T6 ALUMINUM SPECIMENS

Stress Range, psi	Approximate No of Stress Cycles	Residual Strain, $\mu$ in/in. (Average of Two Gages)
26,600 to 34,200 (70 to 90% of MYS)	0	0
	100	1.5
	1,000	2.5
	10,000	3.3
	100,000	3.5
3,800 to 34,200 (10 to 90% of MYS)	0	0
	100	2.0
	1,000	2.5
	10,000	2.8
	55,000	Specimen failed in grips

studied, the permanent set accompanying stress cycling was approximately 3 microinches/inch; this is equivalent to a stress drop of about 30 psi, which is only a fraction of a percent of the steady-stress imposed. At the same time, the failure of the second specimen after 55,000 stress cycles points up one of the dangers inherent in attempting to induce stress relief with mechanical vibrations.

Additional tests are in progress on all three materials: 2014 aluminum, 321 stainless steel, and 1400 beryllium.

#### Measurement of Microcreep at Room Temperature

Flat, pin-loaded specimens of 2014 aluminum and 321 stainless steel were stressed in tension to 90 percent of MYS in Satec creep frames at  $68 \pm 0.25$  F. Creep strain was monitored periodically with a BLH Model 120 strain indicator connected to electric resistance strain gages cemented to both sides of the specimens. Results obtained to date are given in Table 5. It appears that, at 90 percent of the MYS, the aluminum is creeping at a slightly greater rate than is the stainless steel. This contrasts with the thermal cycling stress relaxation tests (Table 2) in which the stainless steel relaxed appreciably more than did the aluminum.

TABLE 5. MICROCREEP DATA

Tests were conducted at  $68 \pm 0.25$  F.

Material	Stress, psi	Elapsed Time, Hrs.	Creep Strain, Microinch/Inch (Average of Two Gages)	
			Specimen 1	Specimen 2
2014-T6 A1	34,200 (90% of MYS)	1	1.5	1.1
		2	2.0	1.3
		4-1/2	2.8	2.0
		7-1/2	3.1	2.2
		23-1/2	5.5	3.9
		77	6.5	4.8
321 SS	8650 (90% of MYS)	1	0.7	0.8
		2	0.8	0.8
		4-1/2	1.0	1.2
		7-1/2	1.2	1.1
		23-1/2	1.4	2.3
		77	1.1	0.5

### DISCUSSION

The results available to date indicate that 2014-T6 aluminum has a number of attractive properties for spacecraft applications in which dimensional stability is important. It has a relatively high MYS-to-density ratio and apparently relaxes very little under moderate thermal cycling or rapid stress cycling when stressed to a high percentage of its MYS. It does exhibit some microcreep, however, when stressed to 90 percent of MYS at 68 F.

The annealed 321 stainless steel appears less attractive for dimensionally critical spacecraft applications. It has a low MYS-to-density ratio and relaxes appreciably under moderate thermal cycling. Its behavior under stress cycling is not yet known. Room temperature creep at 90 percent of MYS does not appear to be significant after 100 hours.

### FUTURE WORK

During the time remaining in the program, work on thermal cycling and stress cycling studies will be continued. The microcreep tests currently in progress will be monitored periodically until the end of the program.